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MULTITAPER CROSS-SPECTRAL ANALYSIS AND RELATED STUDIES OF NTS EXPLOSIONS

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1. SUMMARY

During this report period, software for determining the delay time between two waveforms was further developed and tested on real data. The main improvement was use of the multitaper method of spectral analysis which has been shown to yield better results than standard single-taper procedures. This procedure constitutes a significant improvement over all previous studies of cross-spectral analysis based on the use of a single taper. An application to closely-located Yucca Flat explosions recorded at four stations showed significant improvement over single-taper results. Inter-source coherence for Pn was found to be significantly greater when the two sources lay along the direction of wave propagation than when perpendicular to it. Mean velocities along the four source-receiver paths were found to be stable and significantly different, suggesting that propagation velocities may vary considerably from one path to another. It seems therefore that at least a part of the observed location errors are due to the assumption of a uniform path-independent velocity model in the computation of location. Analysis of data from two closely located explosions suggests that the cross-spectral method may also be used to determine very small differences (of the order of 1%) between propagation velocities of regional phases.

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2. INTRODUCTION

Location relative to a known reference event is often more useful and precise than absolute event location. The use of relative location compensates for most of the errors arising from path effects. Such location requires relative arrival times for pairs of events observed at common stations, which can be obtained with high precision for similar events by waveform cross-correlation. This estimate of the relative time based on the full waveform is generally more precise than that based on rather subjective picks of the initial phase arrival. Conventional cross-correlation slides one waveform past another, and the lag with the optimum correlation coefficient is taken as the relative time. However, the cross-spectral analysis method can yield relative delay times with resolution up to an order magnitude better than the seismogram sampling interval.

Most of the effort during the report period was devoted to developing the software for multitaper. An application to the available data from Yucca Flat explosions demonstrated significant improvement in relative locations. The cross-spectrum method was also applied to regional data from two closely located Pahute Mesa, NTS explosions recorded at two common stations. Preliminary results suggest that the analysis can detect very small differences (of the order of 1%) in the propagation velocities of regional phases generated by the two shots. A knowledge of these differences may be useful in a comparison of the near-source properties of closely located explosions.

3. CROSS-SPECTRAL ANALYSIS WITH MULTITAPER

Single taper cross-spectral analysis of regional data from Yucca Flat explosions with precisely known locations provided relative locations that were accurate to within about 1 km. However, locations based on arrival times determined by alignment of the first peaks were found to be somewhat better (Gupta and Davis, 1992). A possible reason for this disappointing performance was suspected to be the use of a cosine taper on rather short signal windows. We therefore applied the multitaper method of spectral analysis which has been shown to yield better results than standard single-taper procedures (Park *et al.*, 1987; Zhu *et al.*, 1989).

We employed the multitaper method, based on a family of tapers which are resistant to spectral leakage, by mainly following the procedure described by Park *et al.* (1987) and Vernon *et al.* (1991). A set of k tapers $v_n^k(n, w)$ are generated which are functions of the time series length n and the specified inner bandwidth w . The tapers are the eigenvectors of the Toeplitz matrix with associated eigenvalues λ_k . Following Park *et al.* (1987), w was selected to be 4, and only those tapers with λ_k greater than 0.9 were used. With these two restrictions, k was found to be equal to 7, independent of the number of points in the signal window.

Consider two signals A and B represented by the time series $f_a(t)$ and $f_b(t)$, respectively. The signals are windowed (e.g. 64 or 128 samples of data), calibrated, demeaned, and detrended, providing the signals $X_a(n)$ and $X_b(n)$, respectively, where n is the number of samples in the selected window. Let $Y_a^k(N)$ and $Y_b^k(N)$ represent the Fourier transforms of $v_n^k X_a(n)$ and $v_n^k X_b(n)$, where $N = \frac{n}{2} + 1$, respectively.

An adaptive spectral estimate of $f_a(t)$, \hat{S}_a is formed by

$$\hat{S}_a = \frac{\sum_k |d_a^k(N) Y_a^k(N)|^2}{\sum_k |d_a^k(N)|^2} \quad (1)$$

where the weights d_a^k , which depend on frequency (N) and on the taper order k, are chosen to reduce bias from spectral leakage. An initial spectral estimate is made by assuming

$$\hat{S}_a = \frac{|Y_a^1|^2 + |Y_a^2|^2}{2} \quad (2)$$

The first guess for weights is then made by

$$d_a^k(N) = \frac{\sqrt{\lambda_k} \hat{S}_a}{\lambda_k \hat{S}_a + (1-\lambda_k) \sum_{i=1}^n [X_a(i)]^2} \quad (3)$$

A new spectral estimate of \hat{S}_a is made by inserting the weights from equation (3) into equation (1) and using this new value into equation (3) to compute the corresponding new weights. This process is repeated until the difference between two successive \hat{S}_a is less than 0.0001. Once the weights have been determined, the multitaper cross-spectrum is computed from:

$$Y_{ab} = \frac{\sum_k (\lambda_k)^{-1} \sum_k \lambda_k d_a^k(N) Y_a^k(N) d_b^k(N) Y_b^{k*}(N)}{k \left[\sum_k (d_a^k(N))^2 \right]^{1/2} \left[\sum_k (d_b^k(N))^2 \right]^{1/2}} \quad (4)$$

where * indicates the complex conjugate. If Y_{ab} is expressed as

$$Y_{ab}(N) = \text{Re}(N) + i \text{Im}(N), \quad (5)$$

the phase spectrum $\phi(N)$ is

$$\phi(N) = \tan^{-1} \frac{\text{Im}(N)}{\text{Re}(N)} \quad (6)$$

If the two seismograms are identical in shape but have different amplitudes and are shifted in time by τ , then

$$f_b(t) = k f_a(t+\tau), \quad (7)$$

and by the application of the shift theorem, the phase spectrum becomes

$$\phi(N) = 2 \pi N \tau \quad (8)$$

Thus the delay time τ can be obtained simply by fitting a straight line through the phase of the cross-spectrum with zero intercept. In fitting this slope, the values are weighted based on the coherence γ_{ab} :

$$\gamma_{ab}^2 = \frac{|Y_{ab}|^2}{Y_{aa} Y_{bb}} \quad (9)$$

The weighting factor, $W(N)$ in the linear fit is based on the Hannon-Thomson processor (Knapp and Carter, 1976), *i. e.*

$$W(N) = \frac{\gamma_{ab}^2(N)}{1 - \gamma_{ab}^2(N)} \quad (10)$$

The slope of the line has a continuum of possible values, rather than discrete values, with the result that estimates of delay time for highly coherent pairs can actually be an order of magnitude more precise than the sample rate. This technique has been applied successfully to local sequences of earthquakes with impressively precise locations (Ito, 1985; Fremont and Malone, 1987).

Regional data from six closely spaced underground nuclear explosions at the Nevada Test Site (NTS), recorded at the four broadband digital stations, ELK, KNB, LAC, and MNV (Table 1 and Figure 1), have been analyzed to determine how the cross-spectral method may best be used to improve relative locations. For these explosions, with precisely known locations, the near-source geological and geophysical properties are also known so that the influence of parameters such as shot depth and geological environment can also be investigated. Software for determining the delay time between two waveforms has been developed and tested. The relative arrival times between two events recorded at a common station are determined with a precision of 0.001 sec. As an example, results from the vertical component

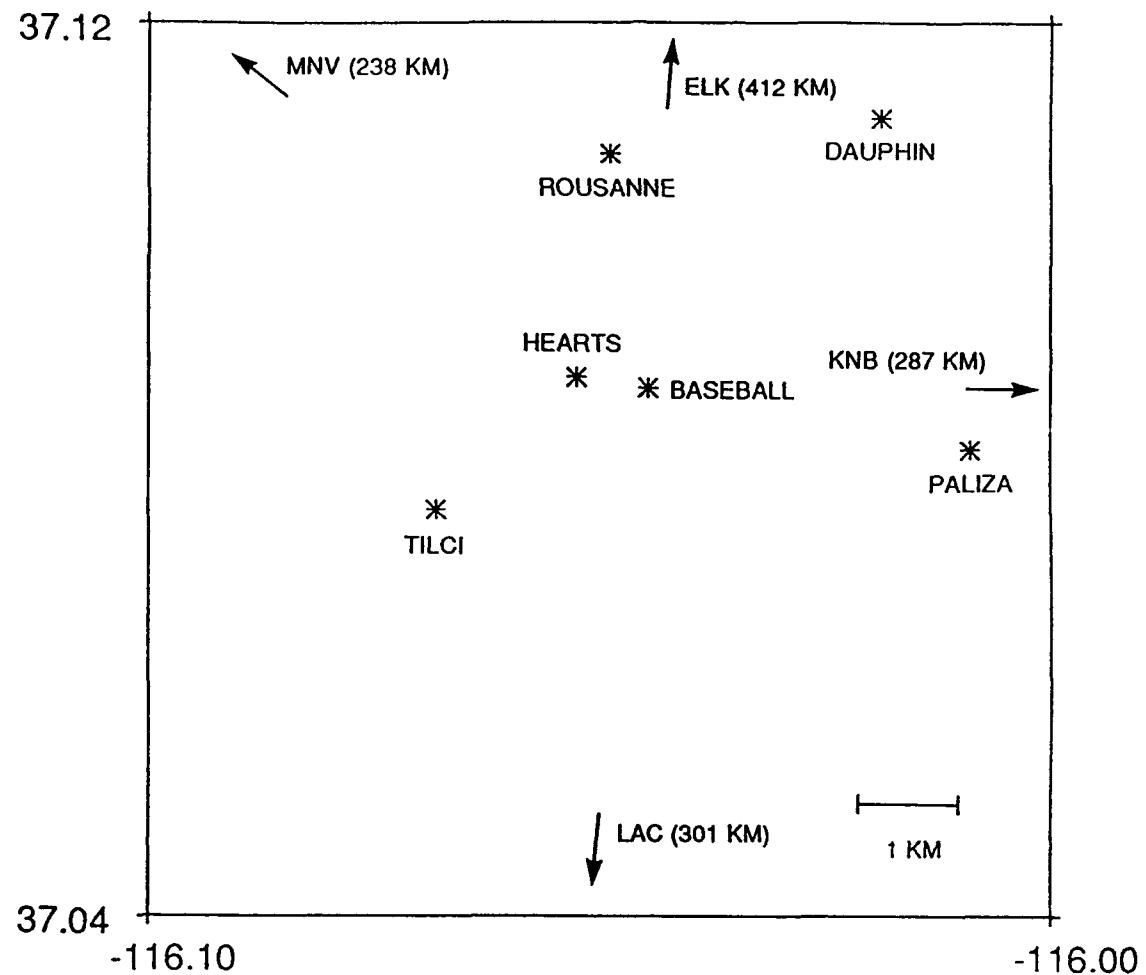


Figure 1. Map of six Yucca Flat explosions used in the study. Azimuthal directions and distances from BASEBALL to the four recording stations are indicated.

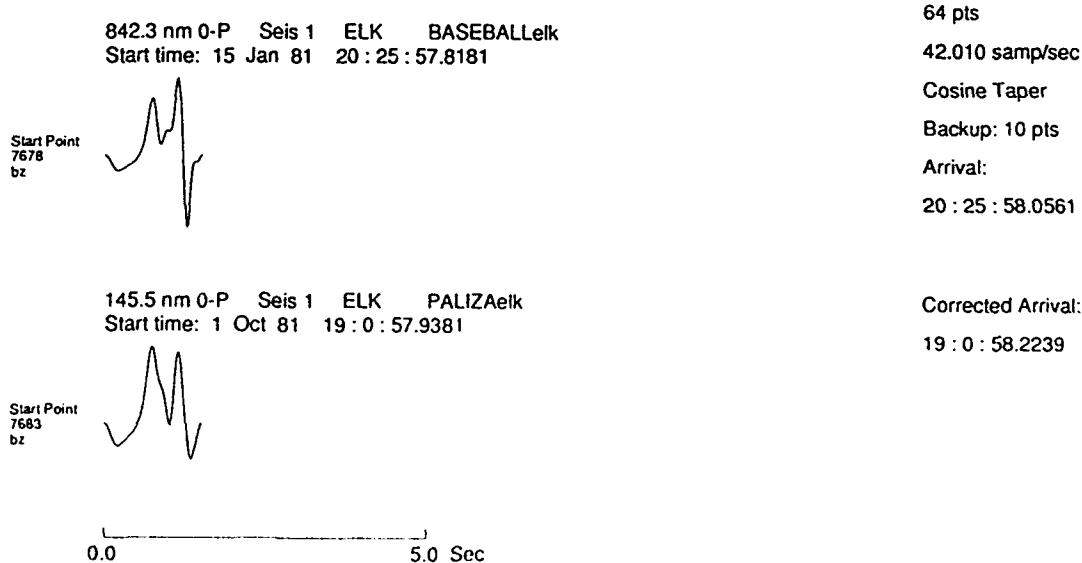
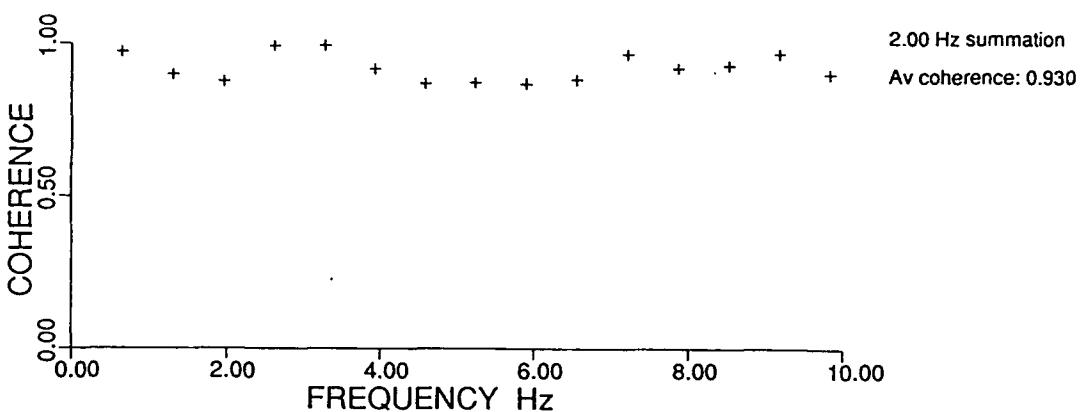
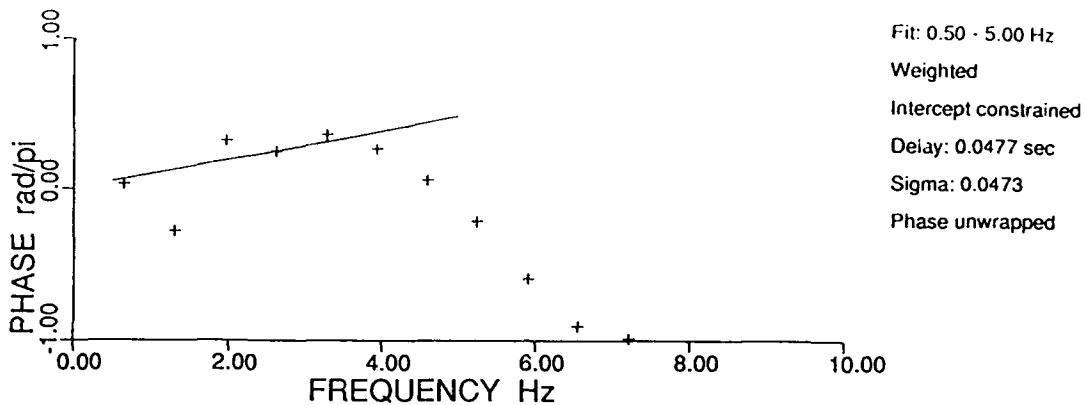
ELK records of the Yucca Flat explosions BASEBALL and PALIZA are shown in Figure 2. The digital data are sampled at 42 samples/sec and the signal window is 64 points (about 1.5 sec). Figure 2 (bottom) shows the input waveforms which may be selected to be of any desired duration. The signal window over which a cosine taper applies is also variable. The top plot shows the phase of the cross-spectrum varying between $-\pi$ and $+\pi$ whereas the lower plot shows the coherency, varying between 0 and 1, derived by using a bandwidth of 2.0 Hz. The delay time of 0.0477 (0.0473) sec is simply the slope of the phase of the cross-spectrum over the specified range of 0.5-5.0 Hz and is obtained by fitting a slope through 0, using a weighting scheme based on coherence of the cross-spectrum (equation 10); the quantity within parentheses denotes one standard deviation.

TABLE 1
6 YUCCA FLAT EXPLOSIONS USED IN STUDY

No.	DATE	NAME	m_b	P-WAVE	SHOT	DEPTH
				VEL (KM/S)	DEPTH (KM)	OF WT (KM)
1	06 Sep 1979	HEARTS (B)	5.892	1.763	0.6400	0.5070
2	14 Nov 1980	DAUPHIN (A)	4.554	1.420	0.3200	0.5800
3	15 Jan 1981	BASEBALL (B)	5.725	1.970	0.5639	0.5120
4	01 Oct 1981	PALIZA (A)	5.115	1.497	0.4724	0.5300
5	11 Nov 1981	TILCI (A)	5.035	1.600	0.4450	0.4940
6	12 Nov 1981	ROUSANNE (B)	5.458	1.580	0.5182	0.4950

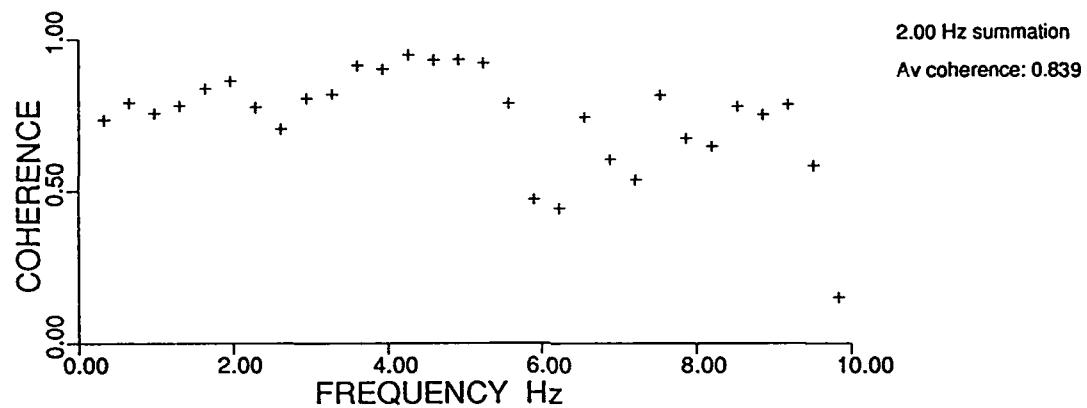
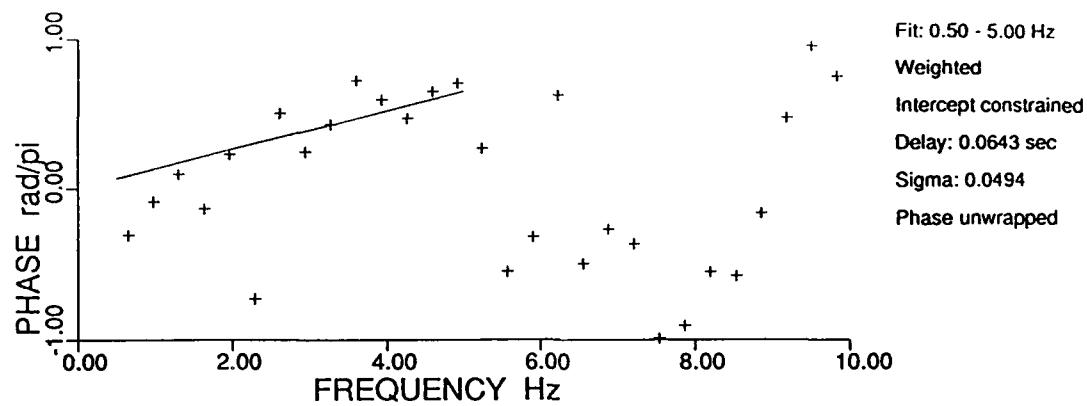
Note: B and A denote shots below and above the water table, respectively.

Figure 3 shows results of cross-spectral analysis when the signal window is doubled to 128 points. A comparison with Figure 2 shows a decrease in the average coherency and an increase in the delay time. Results when the cosine tapers in Figures 2 and 3 are replaced by multitaper are shown in Figures 4 and 5, respectively. Note the significant improvement in



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Figure 2. Cross-spectral analysis for measuring delay times based on use of the cosine taper. The two input waveforms at ELK (bottom), each 64 points long, provide the phase of the cross-spectrum (top) and coherence based on bandwidth of 2.0 Hz for frequencies up to 10 Hz. Mean slope of the phase spectrum, averaged over the indicated frequency range of 0.5-5.0 Hz, provides the delay time used to obtain the corrected arrival time for PALIZA.



1187.8 nm 0-P Seis 1 ELK BASEBALLelk
Start time: 15 Jan 81 20:25:57.8181



128 pts
42.010 samp/sec
Cosine Taper
Backup: 21 pts
Arrival:
20:25:58.3180

362.9 nm 0-P Seis 1 ELK PALIZAelk
Start time: 1 Oct 81 19:0:57.9381

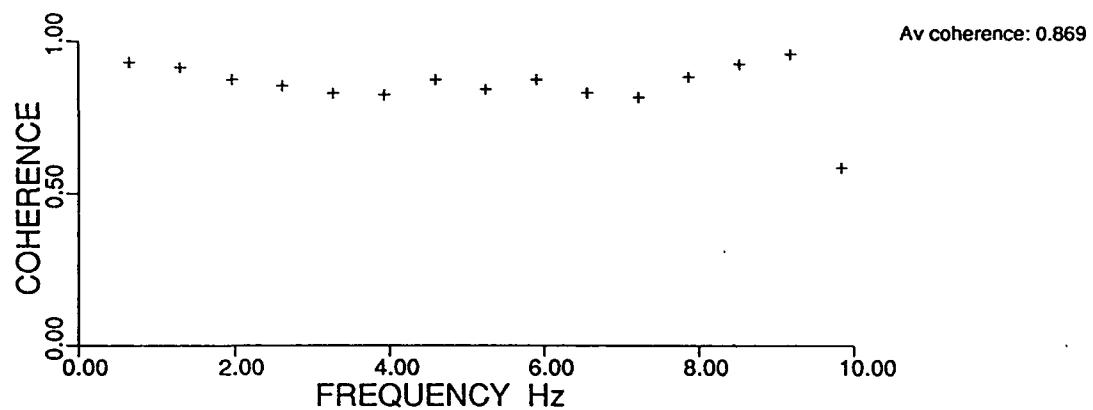
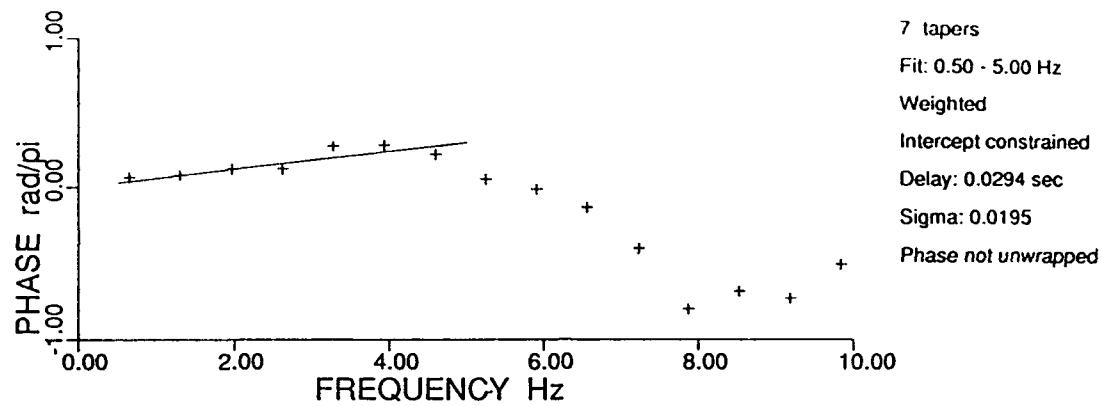


Corrected Arrival:
19:0:58.5023

0.0 5.0 Sec

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Figure 3. Similar to Figure 2 for signal windows of 128 points.

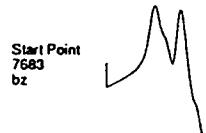


842.3 nm 0-P Seis 1 ELK BASEBALLelk
Start time: 15 Jan 81 20:25:57.8181



64 pts
42.010 samp/sec
Backup: 21 pts
Arrival:
20:25:58.3180

195.8 nm 0-P Seis 1 ELK PALIZAelk
Start time: 1 Oct 81 19:0:57.9381

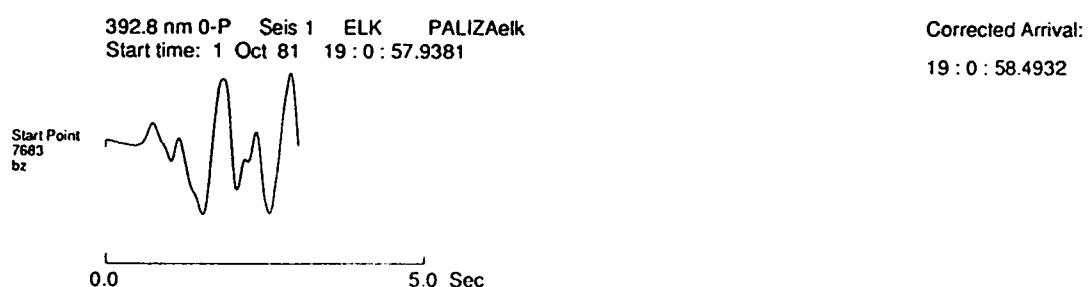
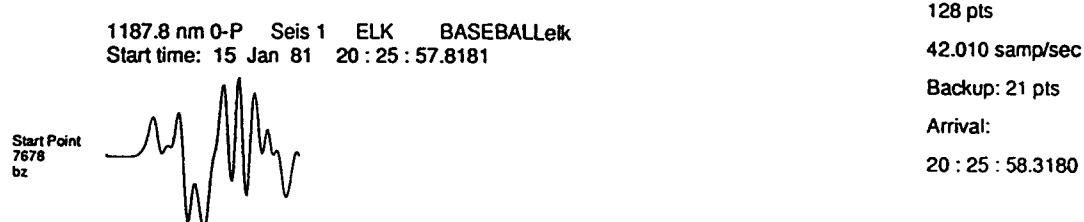
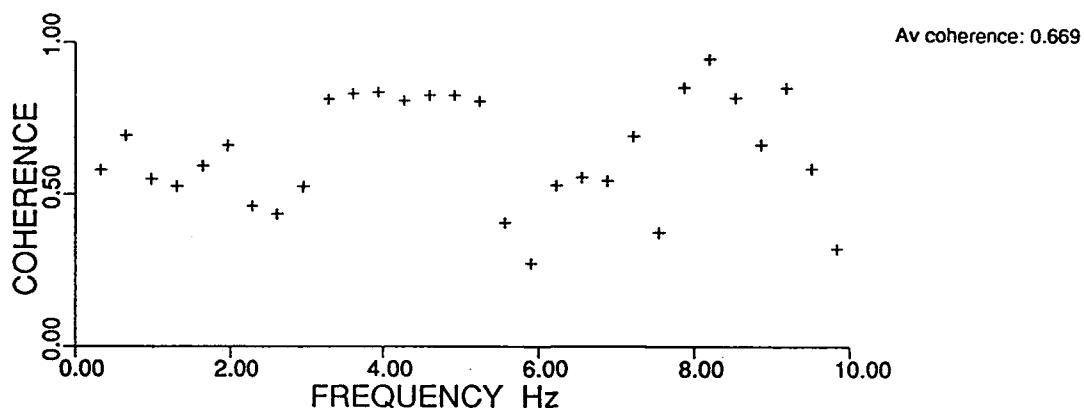
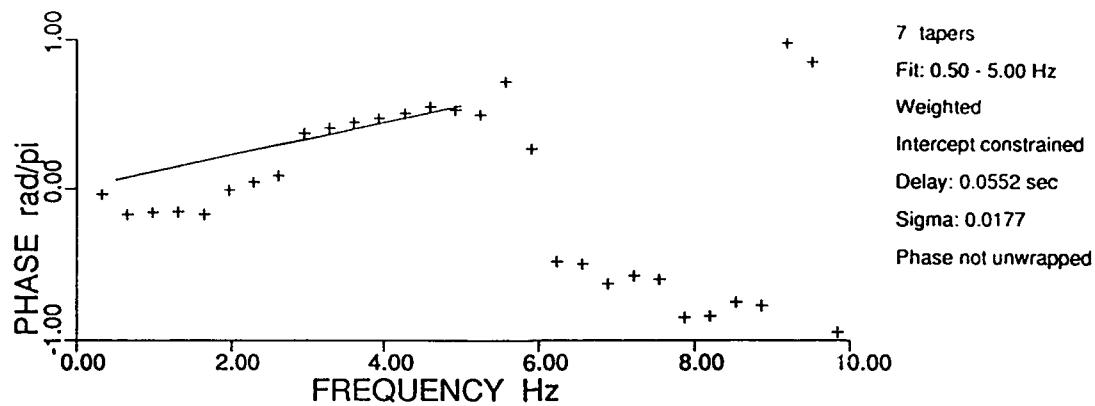


Corrected Arrival:
19:0:58.4674

0.0 5.0 Sec

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Figure 4. Similar to Figure 2 based on use of the multitaper (seven tapers).



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Figure 5. Similar to Figure 2 based on use of the multitaper and signal windows of 128 points.

the determination of delay times as indicated by the improved fits of mean slope and the reduced values of standard deviation.

Assuming BASEBALL to be the reference shot with known location and its first peak at each station as the reference time, cross-spectral analysis was carried out to obtain the corrected arrival times (such as those indicated on Figures 2, 3, 4, and 5) for each explosion recorded at the four stations. Results based on use of the cosine taper and signal windows of 128 points were first determined. For each explosion, the four arrival times are used as input to the LOCATE feature of the Analyst Review Station (ARS) to obtain the epicentral location and the origin time. The arrival times (without any delay correction) for BASEBALL recorded at the four stations are also used to compute the corresponding ARS location. The ARS computed locations and the actual (known) locations of six explosions are shown in Figure 6. The ARS computed locations for the five shots (paired with BASEBALL) are shifted by the amount of shift between the ARS computed and actual locations of BASEBALL. A comparison of the shifted locations of each of the five shots with its actual location provides the location error associated with each shot (Figure 6). The mean location error is only 1.32 (0.61) km. Cross spectral analysis based on the use of longer (256 points) windows was also carried out for the same six explosions. Using a bandwidth of 1.0 Hz for deriving coherency and a frequency range of 0.5-5.0 Hz for computing the delay time, the location results were found to be very similar to those in Figure 6 in both the magnitude and azimuthal direction of the location errors; the mean location error was 1.22 (0.61) km.

Locations based on the use of arrival times determined by simple alignment of the first peaks at common stations are shown in Figure 7. A comparison with locations derived by using the cross-spectral analysis (Figure 6) shows significant improvement, especially for the

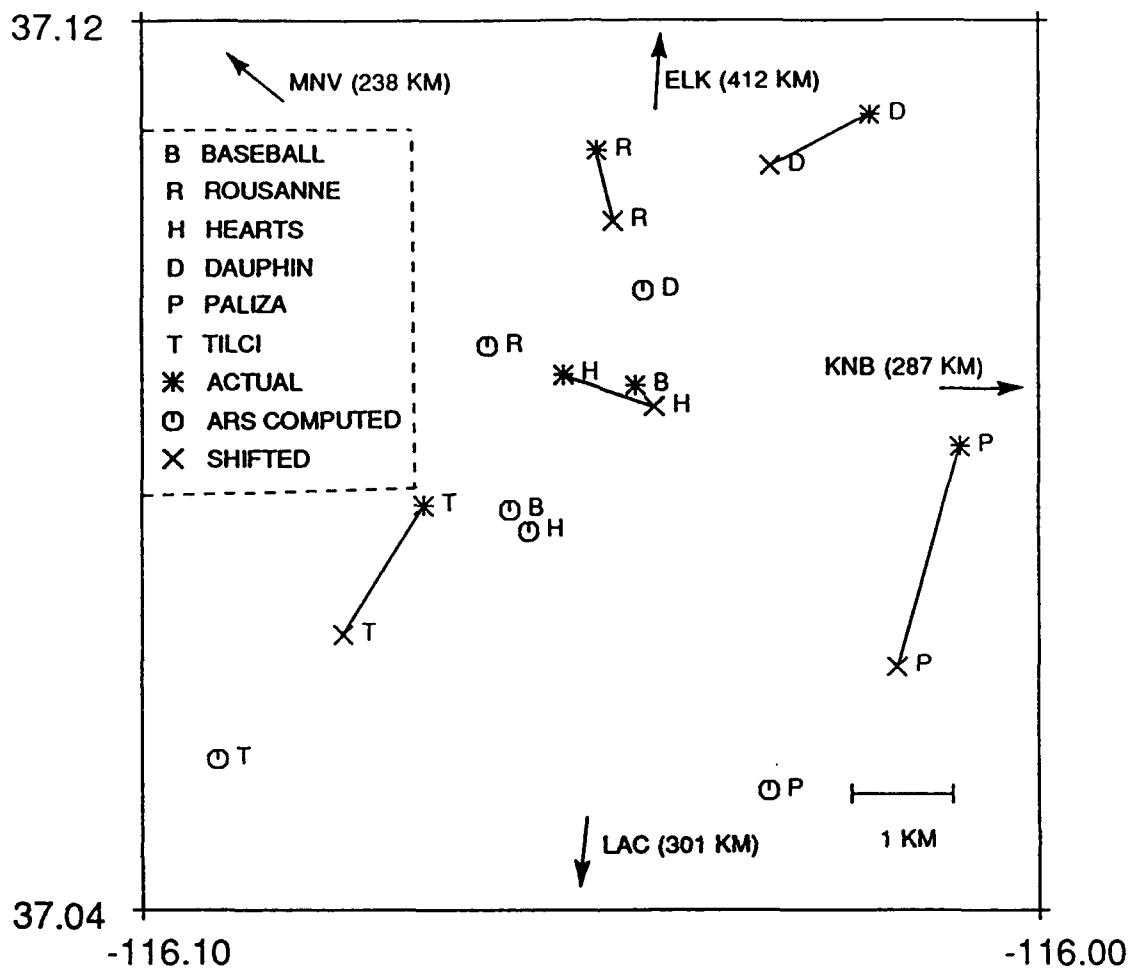


Figure 6. Location results for six Yucca Flat explosions based on arrival times derived from cross-spectral analysis using the cosine taper and signal windows of 128 points. Actual locations, ARS computed locations, and locations with shift based on BASEBALL are shown; the five lines indicate the error between the actual and computed locations. Mean location error is 1.318 (0.614) km.

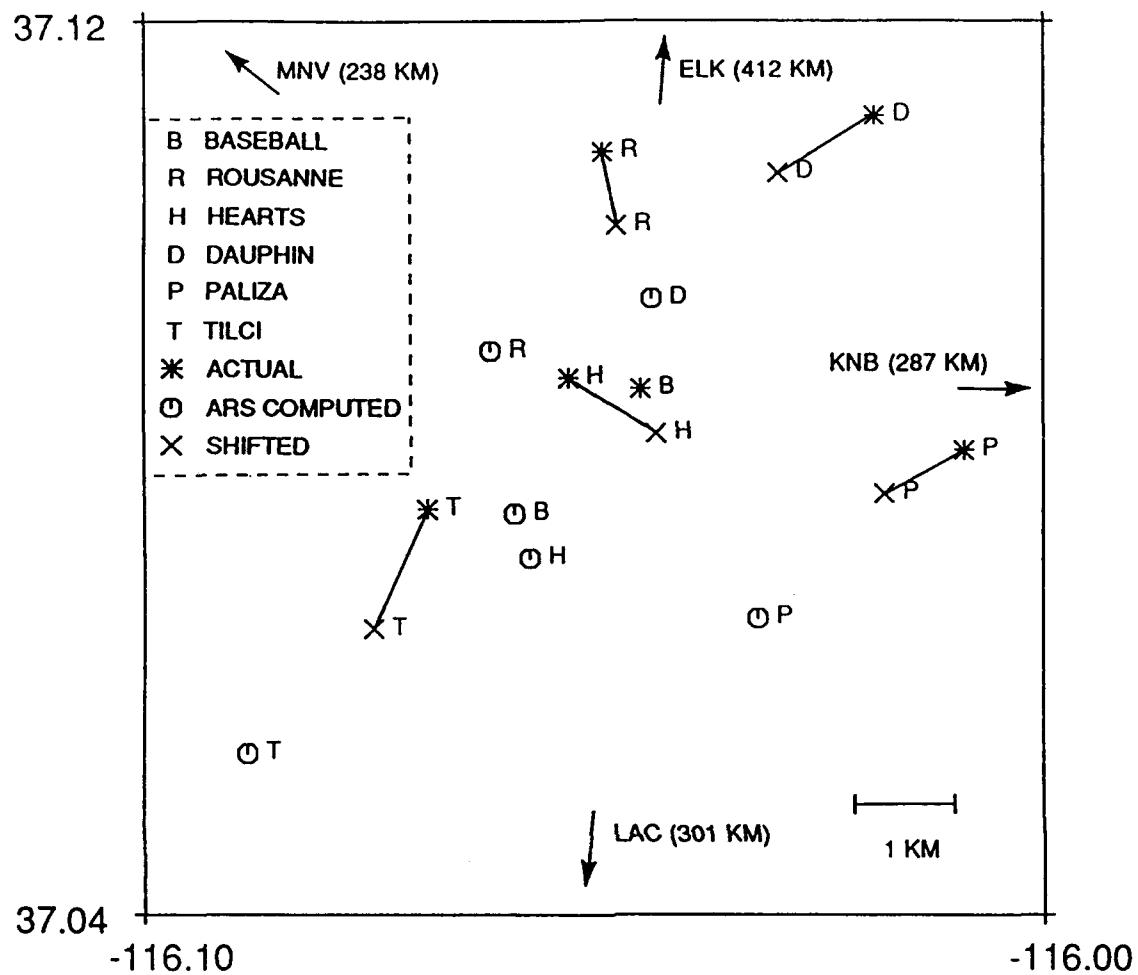


Figure 7. Similar to Figure 6 but derived from simple alignment of the first peaks of all explosions recorded at the four recording stations. Mean location error is 1.017 (0.218) km.

two shots PALIZA and TILCI. The mean location error is only 1.017 (0.218) km. Possible reasons for the smaller accuracy of the cross-spectral analysis are the spectral leakage and variability for the estimates expected when cosine taper is used on rather short time series (Vernon *et al.*, 1991).

Location results based on use of the multitaper and signal windows of 64 points are shown in Figure 8. There is significant improvement compared to the results with cosine taper (Figure 6); the mean location error is 1.010 (0.221) km. These results appear to be impressive if one considers the large epicentral distances (about 200 km to 400 km) and the complex geology of the Nevada test site.

Analysis of regional data from Yucca Flat explosions also provides valuable information regarding inter-source coherence of closely located explosions recorded at common stations. A comparison of the coherency plots in Figures 2 and 3 or Figures 4 and 5 indicate that the shorter signal windows of Pn have significantly better coherency over a much larger range of frequency than the longer windows. This implies that the first arrivals in Pn are considerably more similar than the later arriving phases, perhaps due to greater contamination by later-arriving scattered energy. Furthermore, inter-source coherence for Pn appears to be significantly greater when the two sources lie along the direction of wave propagation than when perpendicular to it. This is illustrated by comparison of coherence at ELK and KNB for two pairs of explosions BASEBALL and ROUSANNE (Figure 9) and BASEBALL and PALIZA (Figure 10). These results were based on use of the multitaper and signal windows of 128 points. For BASEBALL and ROUSANNE, ELK and KNB are nearly along and perpendicular to the direction of wave propagation, respectively. On the other hand, for BASEBALL and PALIZA, ELK and KNB approximate directions perpendicular to and along the

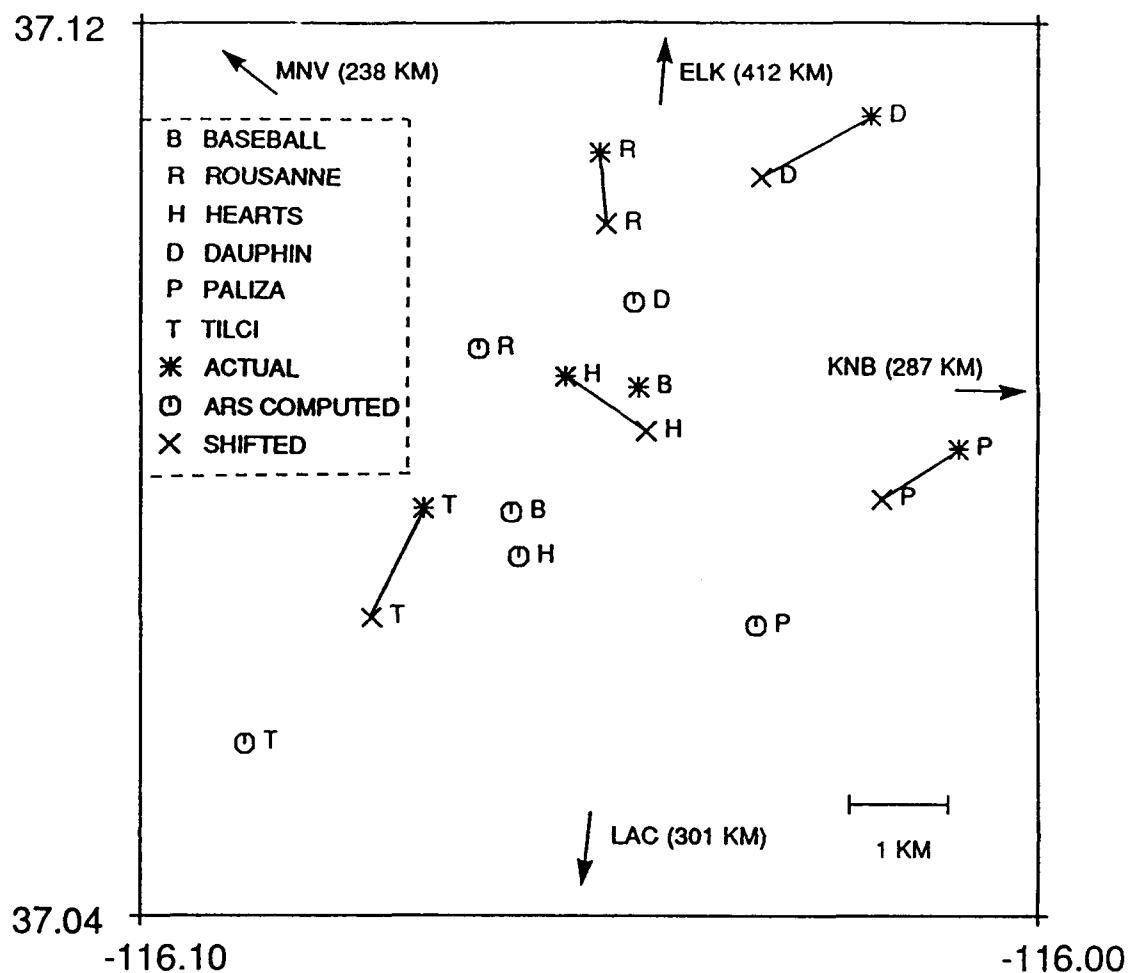
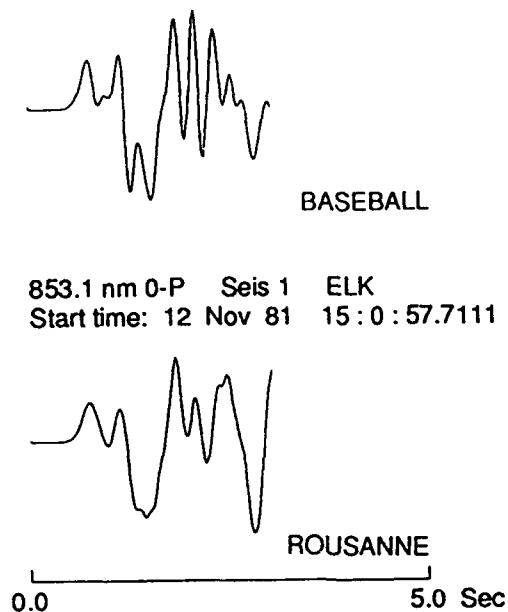


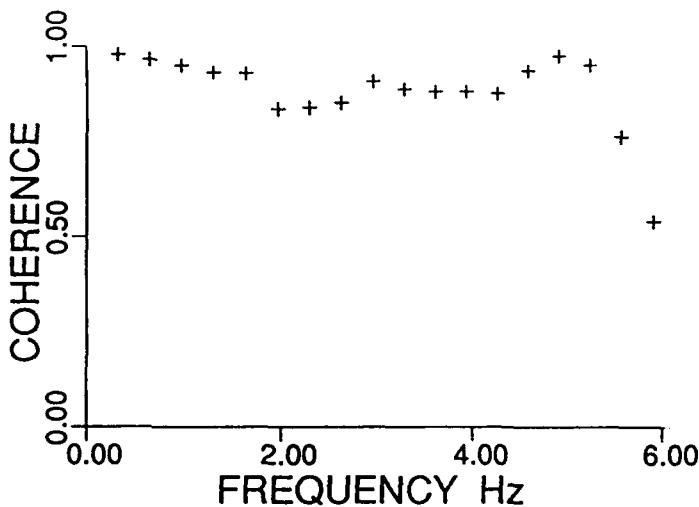
Figure 8. Similar to Figure 6 but derived from cross-spectral analysis based on use of the multitaper and signal windows of 64 points. Mean location error is 1.010 (0.221) km.

1187.8 nm 0-P Seis 1 ELK
Start time: 15 Jan 81 20:25:57.8181

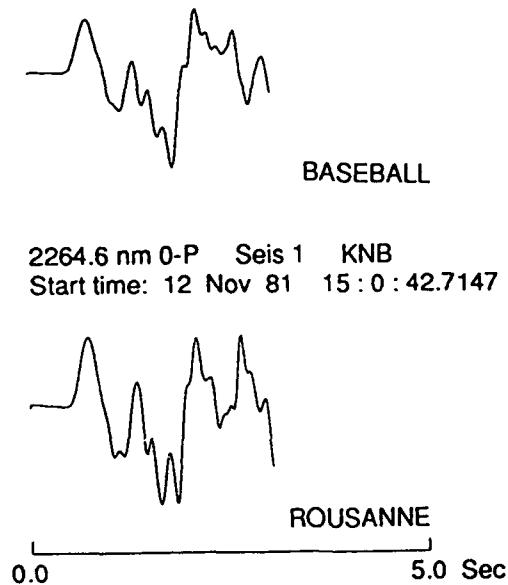


(a)

AVERAGE COHERENCE (0.1-3.0 HZ) = 0.909



3972.5 nm 0-P Seis 1 KNB
Start time: 15 Jan 81 20:25:42.6075



(b)

AVERAGE COHERENCE (0.1-3.0 HZ) = 0.848

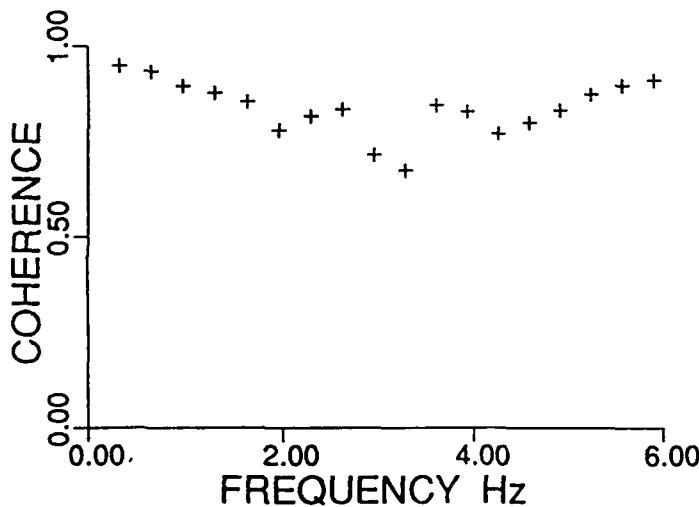
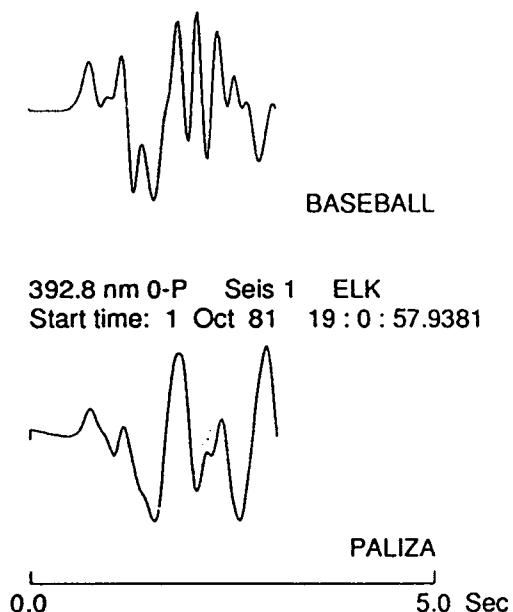


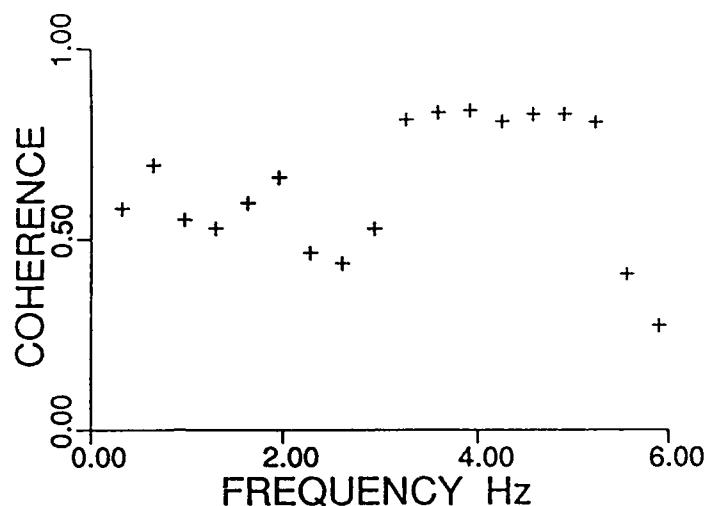
Figure 9. Waveform and coherency plots for BASEBALL and ROUSANNE recorded at ELK and KNB showing the inter-source coherency for Pn (over the frequency range of 0.1-3.0 Hz) to be larger when the two sources lie nearly along the direction of wave propagation than when approximately perpendicular to it.

1187.8 nm 0-P Seis 1 ELK
Start time: 15 Jan 81 20:25:57.8181

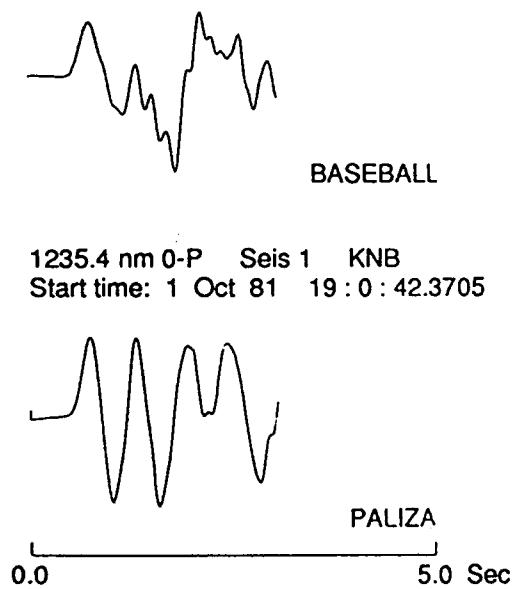


(c)

AVERAGE COHERENCE (0.1-3.0 Hz) = 0.558



3972.5 nm 0-P Seis 1 KNB
Start time: 15 Jan 81 20:25:42.6075



(d)

AVERAGE COHERENCE (0.1-3.0 Hz) = 0.630

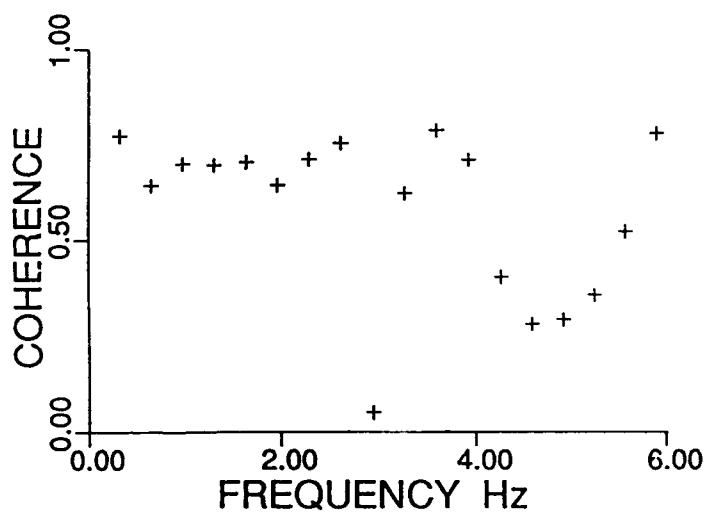


Figure 10. Waveform and coherency plots for BASEBALL and PALIZA recorded at ELK and KNB, again showing the inter-source coherency for Pn (over the frequency range of 0.1-3.0 Hz) to be larger when the two sources lie nearly along the direction of wave propagation than when approximately perpendicular to it.

wave propagation. These results, based on use of the multitaper and signal windows of 128 points, are similar to the inter-sensor coherence of regional phases generally observed to be greater along the radial direction than along the transverse direction. An attempt will be made to exploit these coherency differences to improve locations. Analysis of the Lg phase showed the inter-source coherence to be significantly smaller than for Pn, again similar to the observed inter-sensor coherence results for Lg and Pn. Also, coherency appeared to vary significantly from one station to another.

In order to understand what causes the discrepancy between the actual locations and those computed from observations of Pn from the Yucca Flat explosions, we examined the lateral variations in the Pn velocity under the test site. Pn arrival times from closely spaced explosions can be used to estimate average velocities to various stations if the spatial locations of the explosions are precisely known and data from at least two shots are available.

Consider a number of closely located sources, S_i recorded at a number of well-separated receivers, R_j . Let the average P-wave velocities from the limited source region to the relatively distant receivers be α_j . If r_{ij} represents the distance from source S_i to the receiver R_j and z_i are the origin times of the various sources, then the P-wave arrival times, T_{ij} are given by

$$T_{ij} = \frac{r_{ij}}{\alpha_j} + z_i \quad (11)$$

Having data from two or more sources at two or more receivers, we can solve for α_j by using the method of least squares.

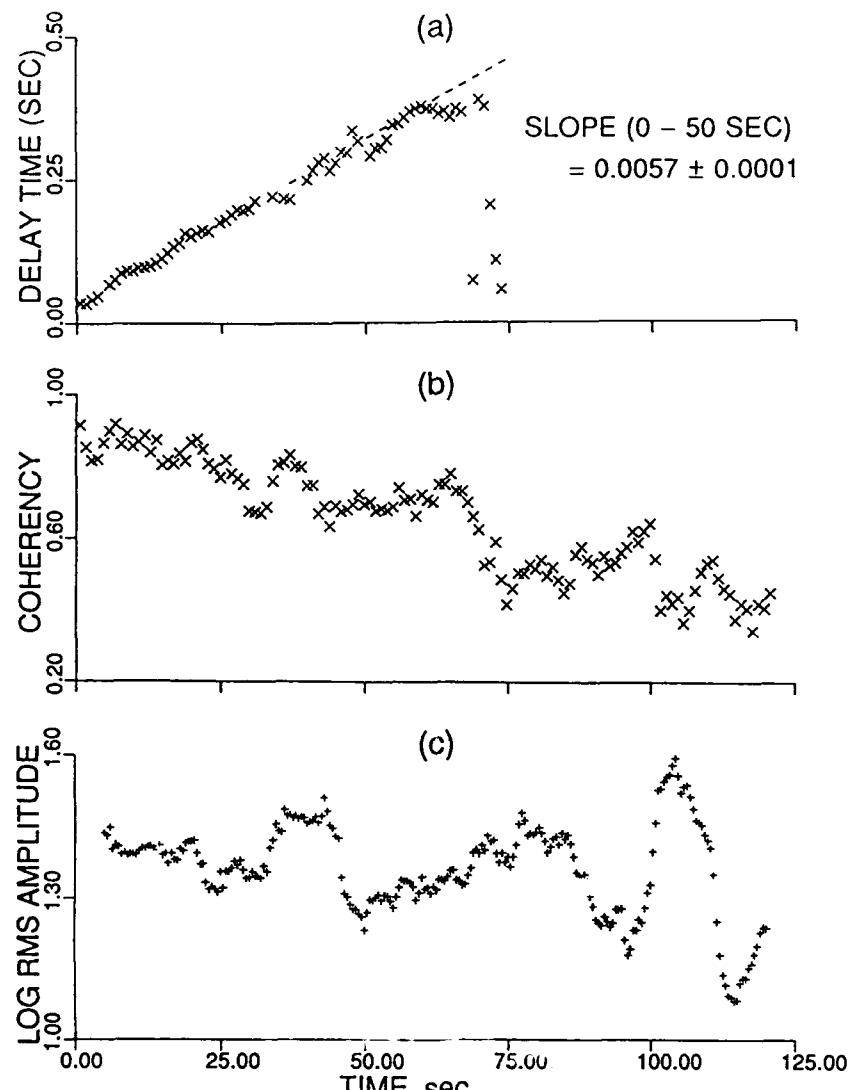
Using Pn arrival times, based on alignment of the first peaks, from six explosions (Table 1) recorded at the four stations, the mean velocities to the four stations ELK, KNB, LAC, and

MNV were determined to be 7.051 (0.006), 6.636 (0.007), 6.767 (0.007), and 6.469 (0.008), respectively. The quantities within parentheses, denoting one standard deviation of the mean, are remarkably small so that the velocity differences are significant and outside the margin of error. The large differences in mean velocities (maximum about 9%) along the four source-receiver paths suggest that propagation velocities may vary considerably from one path to another. Moreover, our results indicate velocities along the north-south direction to be somewhat larger than those along the east-west direction, in general agreement with the tectonics of the region and the velocity measurements of Harmsen (1992). It seems therefore that at least a part of the observed location errors are due to the assumption of a uniform path-independent velocity model.

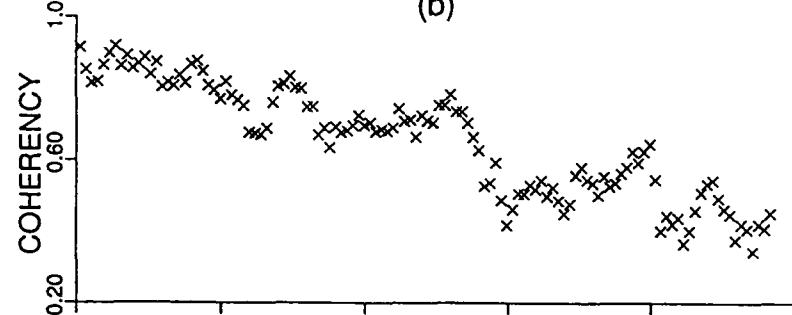
4. COMPARISON OF DATA FROM TWO CLOSELY LOCATED SHOTS

Cross-spectrum analysis has been used to provide a high-precision method for measuring temporal velocity changes in the earth's crust (Poupinet *et al.*, 1987). The method compares the scattered wave portions, or coda, of two highly similar waveforms, generated by a pair of nearly identical sources (called doublets), recorded at the same receiver at different times. By analyzing progressive relative phase delays between the two doublet signals as a function of elapsed time, velocity changes on the order of 0.01% could be measured. The high precision of the doublet method is possible because coda waves from colocated sources will sample the same regions and generally follow paths that increase in length with elapsed time. Thus a small decrease in velocity occurring within the sampled region during the time period between the doublet origin times will produce a relative delay that increases with elapsed time over some portion of the scattered waves. If the velocity change is pervasive, the relative delay may increase linearly over the entire coda. This trend of increasing delay is easier to detect and measure than an isolated delay based on a single arrival. Using active, repeatable sources instead of natural earthquakes, Roberts *et al.* (1992) used the doublet method for measuring small velocity and attenuation changes in solids.

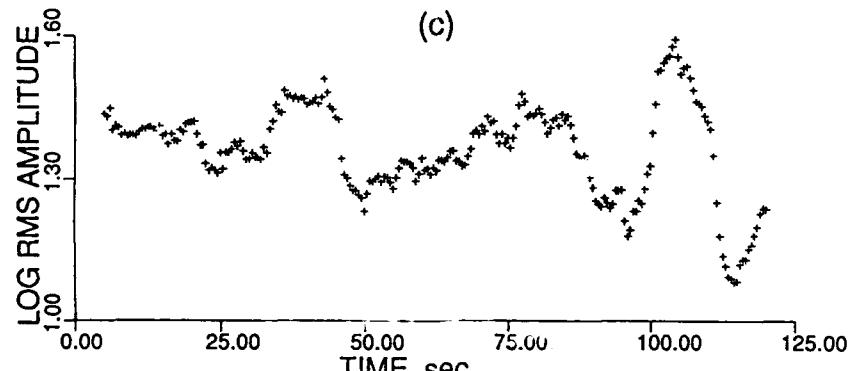
The Pahute Mesa explosions BUTEO (12 May 1965, shot depth 696 m, yield 0.7 kt) and DURYEA (14 April 1966, shot depth 544 m, yield 65 kt) were closely located (probably in the same hole) and generated similar records at two common LRSM stations, KN-UT and MN-NV at epicentral distances of 321 and 201 km, respectively (Blandford, 1976). Using 20 samples/sec data at KN-UT, time delays were measured for overlapping 128-point windows incremented by 1 sec. A plot of the mean slopes of the phase spectra of each window, averaged over the frequency range of 0.5-2.0 Hz, versus the elapsed time is shown in Figure 11a.



(b)



(c)



DURYEA SPZL

8869.7 nm 0-P 0.50 - 2.00 Hz Seismogram 121 L10511

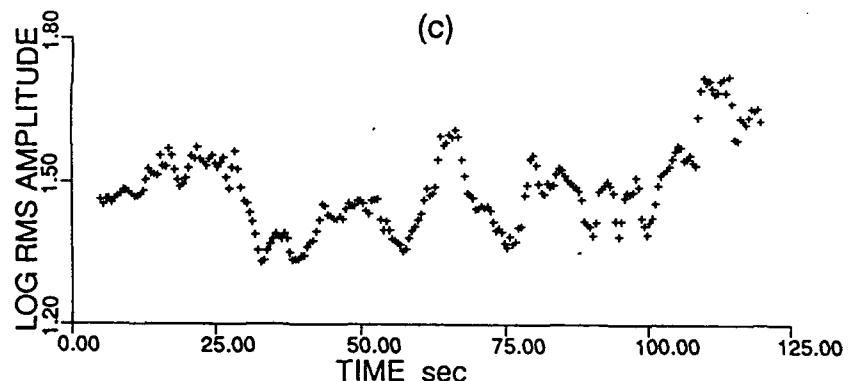
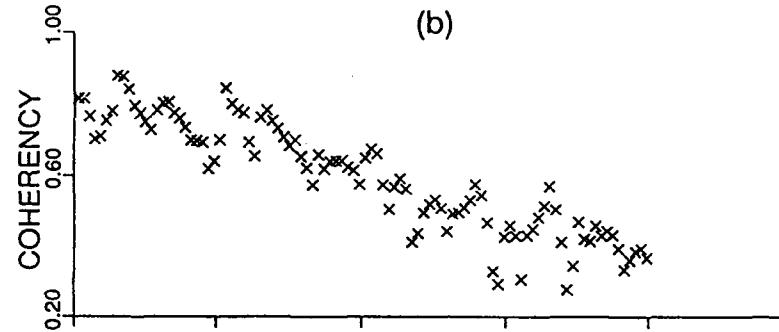
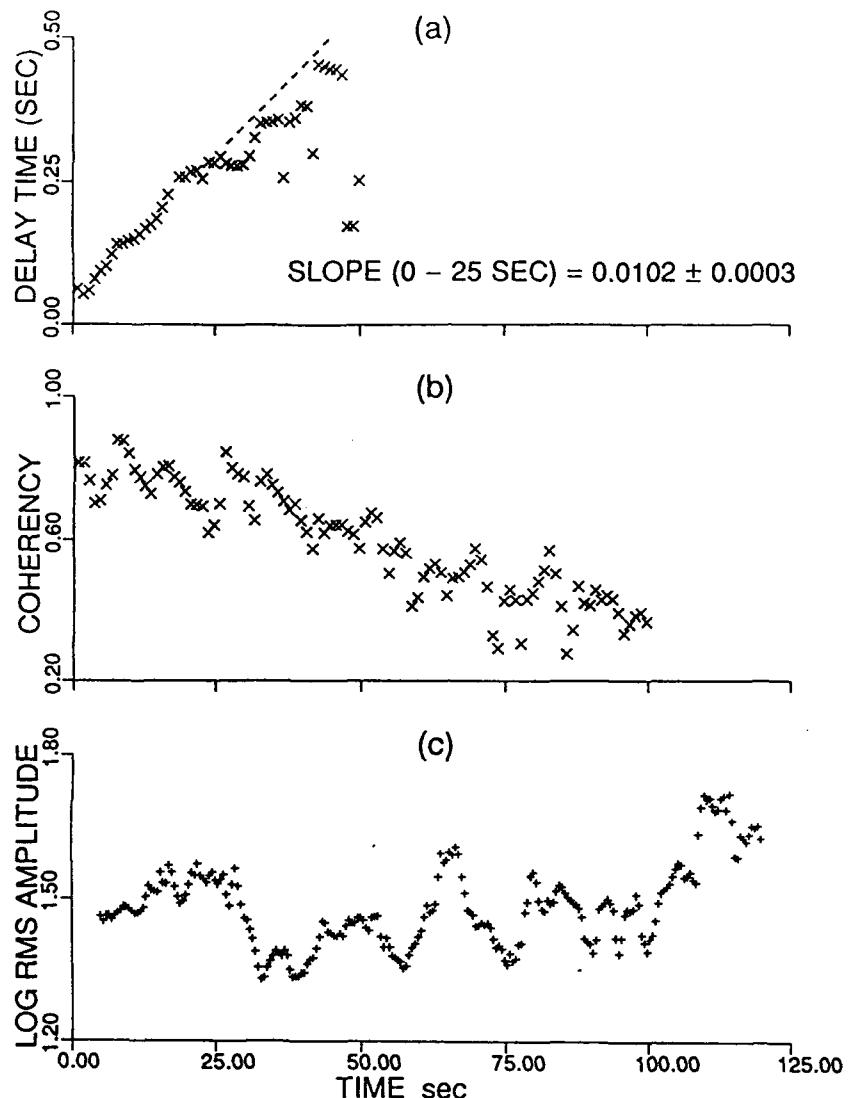
BUTEO SPZH

402.4 nm 0-P 0.50 - 2.00 Hz Seismogram 72 L04702

Figure 11. Comparison of the LRSM station KN-UT records of DURYEA and BUTEO showing (a) delay time, (b) coherency, and (c) differential bandpassed (0.5-2.0 Hz) log-rms amplitude versus time starting about 2 sec before the onset of Pn. Results are based on overlapping windows of length 6.4 sec for (a) and (b) and 10 sec for (c) with incremental shift of 1.0 sec for (a) and (b) and 0.5 sec for (c). Bandpassed waveforms of the two explosions are shown at bottom.

The corresponding coherency is plotted in Figure 11b. In Figure 11a, the mean slope, averaged over the first 50 sec of data, appears to suggest a medium velocity differential of about 0.6%. Bandpassed (0.5-2.0 Hz) log-rms amplitudes, based on overlapping windows of length 6.4 sec and incremental shift of 0.5 sec, were also obtained for the two shots (see Gupta and Wagner, 1992 for more details). Figure 11c shows the differential (DURYEA - BUTEO) log-rms amplitude versus time starting about 2 sec before the onset of Pn. Bandpassed waveforms of the two explosions are shown at bottom.

Results of similar processing of data from the same two explosions recorded at MN-NV are shown in Figure 12. The mean slope in Figure 12a, averaged over the first 25 sec of data, suggests a medium velocity differential of about 1.0%. These results, although preliminary and subject to revision in view of the coherency declining rapidly with time, suggest that the cross-spectral analysis can be used to determine very small differences between similar waveforms of two closely spaced explosions.



DURYEA SPZL

19103.2 nm 0-P 0.50 - 2.00 Hz Seismogram 113 L10511



838.0 nm 0-P 0.50 - 2.00 Hz Seismogram 77 L04702

Figure 12. Similar to Figure 11 for the recording LRSM station MN-NV.

5. CONCLUSIONS

A comparison of relative locations based on application of a single taper versus the multitaper to cross-spectral analysis of regional data from Yucca Flat explosions shows significant improvement when the multitaper is used. An accuracy of about 1 km has been achieved; an impressive result if one considers the large epicentral distances (about 240 and 410 km) and the complex geology around the Nevada Test Site. Inter-source coherence for Pn is found to be significantly greater when the two sources lie along the direction of wave propagation than when perpendicular to it. Mean velocities along paths from the Yucca Flat source region to four stations are found to be stable and significantly different, suggesting that propagation velocities may vary considerably from one path to another. This means that at least a part of the observed location errors are due to the assumption of a uniform path-independent velocity model. Analysis of regional data from two closely located shots suggests that the cross-spectral method may also be used to determine very small differences (of the order of 1%) between propagation velocities of regional phases from pairs of closely spaced explosions.

6. ACKNOWLEDGMENTS

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